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# Investigation of Gasoline Containing GTL Naphtha in a Spark Ignition Engine at Full Load Conditions

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## Abstract

Gas-to-liquid (GTL) naphtha can be used as a gasoline blend component, and the challenge of its low octane rating is solved by using ethanol as an octane booster. However, currently there is little knowledge available about the performance of gasolines containing GTL naphtha in spark ignition engines. The objective of this work is to assess full load performance of gasoline fuels containing GTL naphtha in a modern spark ignition engine. In this study, four new gasoline fuels containing up to 23.5 vol.% GTL naphtha, and a standard EN228 gasoline fuel (reference fuel) were tested. These new gasoline fuels all had similar octane rating with that of the standard EN228 gasoline fuel. The experiments were conducted in an AVL single cylinder spark ignition research engine under full load conditions in the engine speed range of 1000-4500 rpm. Two modern engine configurations, a boosted direct injection (DI) and a port fuel injection (PFI), were used. A comprehensive thermodynamic analysis was carried out to correlate experiment data with fuel properties. The results show that, at the full load operating conditions the combustion characteristics and emissions of those gasoline fuels containing GTL naphtha were comparable to those of the standard EN228 gasoline fuel. Volumetric fuel consumption of fuels with high GTL naphtha content was higher due to the need of adding more ethanol to offset the reduced octane rating caused by GTL naphtha. Results also indicate that, compared to the conventional compliant E228 gasoline fuel, lower particulate emissions were observed in gasoline fuels containing up to 15.4 vol.% GTL naphtha.

26 **Keywords:** GTL Naphtha; Gasoline; Blend Component; Spark Ignition

27

## 28 1. INTRODUCTION

29 The gas-to-liquid (GTL) Fischer Tropsch technology converts natural gas into high-quality liquid  
30 hydrocarbon products that would otherwise be made from crude oil [1]; therefore, the GTL technology  
31 reduces the dependence on crude oil. GTL products include GTL gasoil, GTL naphtha, GTL kerosene,  
32 GTL normal paraffin and GTL base oils [2].

33 GTL gasoil is currently used in compression ignition engines; therefore, it is also named as GTL  
34 diesel [3]. It consists almost exclusively of straight chain normal-paraffins and branched iso-paraffins;  
35 therefore, it has lower concentrations of aromatics, poly-aromatics, olefins. Additionally sulphur and  
36 nitrogen are lower than a conventional diesel. The low poly-aromatic content of GTL diesel are  
37 beneficial to reduce particulate matter (PM) emissions from diesel engines, providing more flexibility  
38 of controlling oxides of nitrogen (NO<sub>x</sub>) emissions by using exhaust gas recirculation (EGR) without  
39 compromising smoke emissions. The low sulphur content leads to a low tendency of deteriorating after  
40 treatment catalysts. The high cetane rating of GTL diesel is beneficial for the diesel engine combustion  
41 [3].

42 A wide range of research has been conducted on the combustion characteristics and emissions of  
43 GTL diesel using single cylinder and multi-cylinder engines, optical engines, and commercial vehicles  
44 under standard testing cycles, and real world driving conditions [4-14]. It has proved that the GTL  
45 diesel has the potential to deliver comparable engine performance and lower emissions to a  
46 conventional diesel without major engine hardware modifications. For example, Nishiumi and Clark et  
47 al. tested a GTL diesel on an in-line four cylinder diesel engines with a modified combustion chamber,  
48 a redesigned injection pattern, and a new EGR calibration [5]. Test results demonstrated that the  
49 combination of the GTL diesel and modified engine had the potential to reduce emissions whilst  
50 keeping the features of diesel engines such as low CO<sub>2</sub> emissions. The after treatment system for near-

zero sulphur GTL diesel fuel was optimised, resulting in improved the catalyst durability performance and higher NO<sub>x</sub> reduction efficiency because the catalyst can be designed to improve a low temperature activity and heat resistance. Clark et al. investigated effects of GTL diesel properties on diesel combustion [7]. Six GTL diesel fuels were formulated with various distillation characteristics and cetane number, and their spray behaviour, mixing characteristics, combustion and emissions were studied. Results showed that fuels with low distillation temperature and a high cetane rating led to reduction of hydrocarbon and particulate emissions, and combustion noise, which was explained by enhanced air/fuel mixing of the lighter fuel, high ignitability and short ignition delay.

Apart from engine combustion characteristics and emissions of GTL diesel fuels, some studies have been carried out focusing on the impact of GTL diesel fuels on fuel injection system. Lacey and Stevenson et al. evaluated the long-term performance of GTL diesel fuels in advanced common rail fuel injection systems [15]. Tests on engine testing cell, and electrically driven common rail pump hydraulic rig tests showed that the performance of GTL diesel was at least comparable to conventional hydrocarbon fuels and superior in a number of areas, and no deposits were produced on fuel injection system components even under severe operating conditions.

GTL naphtha, one of the products from the GTL process, mainly contains a light fraction of C<sub>4</sub> to C<sub>11</sub> hydrocarbons with a high proportion of straight chain paraffins. GTL naphtha is an alternative high-quality feedstock for plastics [2]. As a synthetic product, GTL naphtha has a consistent quality and contains near-zero sulphur and heavy metals, which makes it cleaner [2].

Searching for potential direct uses of GTL naphtha is of interest. Historically, it has not commercially been used in vehicles, because GTL naphtha has a low octane rating, making it unsuitable to be directly blended into conventional gasoline and be used in SI engines. The introduction of bio-ethanol as a blending component has made the octane rating of GTL naphtha a less limiting factor because ethanol has a high octane rating. However, currently there is little knowledge available about the performance of gasolines containing GTL naphtha in spark ignition engines.

In this study, four gasoline fuels containing up to 23.5 vol.% GTL naphtha, three of which were close to being EN228 compliant, were tested in an AVL state-of-art single cylinder gasoline research engine. A standard EN228 gasoline fuel was used as a benchmark for comparison. Two modern engine configurations, a boosted direct injection (DI) and a port fuel injection (PFI), were selected. The tests were conducted under full load condition in the engine speed range of 1000-4500 rpm. The focus was on the assessment of full load combustion characteristics and emissions of these new gasoline fuels with GTL naphtha. A comprehensive thermodynamic analysis was carried out to correlate engine data with fuel properties.

## **2. EXPERIMENTAL SYSTEMS AND METHODS**

### **2.1. ENGINE AND INSTRUMENTATION**

The engine used in this study is an AVL single cylinder 4-stroke spark ignition research engine, of which the specifications and setup are listed and presented in Table 1 and Figure 1, respectively. Its combustion system features a 4-valve pent roof cylinder head equipped with variable valve timing (VVT) systems for both intake and exhaust valves. The cylinder head is equipped with a central-mounted outward opening high pressure piezo direct injector, and a low pressure PFI. The PFI injector is located in the intake manifold pointing towards intake valves. The spark plug is located at the centre of the combustion chamber slightly tilting towards the exhaust side.

The engine is coupled to an electric dynamometer, which is able to maintain the engine at a constant speed ( $\pm 1$  rpm) regardless of engine power outputs. Intake and exhaust plenums with a capacity of approximately 3 L and 50 L are used to stabilize the intake and exhaust flow for this single cylinder engine. The engine is controlled through an IAV FI2RE management system. An AVL Indicom system with inputs from sensors such as high resolution in-cylinder, intake and exhaust pressure transducers is used for real time combustion indication and analysis. A high resolution crankshaft encoder (0.1 °CAD) is used for engine knocking analysis. A Siemens CATs system is used

for signal acquisition and recording, and it communicates with the IAV FI2RE management system and the AVL Indicom. It is also used for controlling air, fuel, coolant and oil conditioning units, and emission measurement equipment.

A Kistler pressure transducer used for cylinder pressure measurement is installed in a sleeve on the intake and exhaust bridge. Cylinder pressure is collected via a charge amplifier (ETAS ES630.1) with a resolution of 0.1 °CA between 30 °CAD before top dead centre (BTDC) and 70 °CAD after top dead centre (ATDC), and a resolution of 1 °CA in the rest of the cycle. Some key temperature and pressure measurement points are briefly labelled as ‘T’ and ‘P’, respectively, and are shown in Figure 1. The shaft encoder used in this study is a 365C Angle Encoder Set provided by AVL. It is a high precision sensor for angle-related measurements mainly for indicating purposes.

An external air handling device, capable of delivering up to 0.3 MPa boosted air, is used in this study. Air is firstly filtered and dried, and then is delivered to a conditioning system with a capacity of approximately 200 L, in which its pressure and temperature can be precisely close-loop controlled. Temperatures of fuel, coolant and oil are also precisely controlled by individual AVL conditioning units.

Fuel consumptions are measured by an AVL fuel mass flow meter. Gaseous emissions are measured using a Horiba MEXA-7100D gas analyser. Particulate mass (PM) and particulate number (PN) emissions are measured using an AVL Micro Soot Sensor and an AVL 489 Advanced Particle Counter, respectively. The exhaust is sampled 5 m downstream of the exhaust ports, just after the exhaust back pressure regulator via heated lines (maintained at 464 K) to the analysers.

## 2.2. FUELS

Table 2 lists physiochemical properties of fuels (additive free) used in this study. Fuel A (reference fuel) was a typical EN228 compliant gasoline, and Fuels B-E had similar octane rating with Fuel A. Fuel B contained 7.3 vol.% GTL naphtha but no ethanol. Fuels C-E were blends of various

refinery streams, GTL naphtha (12.8 vol.% - 24 vol.%), and ethanol (5 vol.% - 20 vol.%). Fuels B-D were almost EN228 compliant; however Fuel E had an oxygen content of 7.2 wt.%, which exceeded the EN228 upper limit of 3.7 wt.%.

### 2.3. ENGINE CONFIGURATIONS AND EXPERIMENTAL PROTOCOL

DI and PFI engine configurations were selected for fuels' performance assessment. In both engine configurations, the compression ratio was 9.5:1. Table 3 lists the test protocol. Full power tests with engine speeds ranging from 1000-4500 rpm were tested under defined intake manifold pressure. Under the compression ratio of 9.5:1, the maximum intake manifold pressure tested in this study was 0.2 MPa. The parameters, such as intake and exhaust valve timing, and injection strategy (see Table 3), were optimised for Fuel A and used for all other fuels. In this study, all the fuels were designed with similar octane ratings, it is expected that the optimised spark timing for all fuels would be similar; therefore, it was decided that the optimised spark timing map for Fuel A was used for all fuels. Additionally, comparing combustion characteristics under the same spark timing maps for all fuels make it possible to evaluate the burning speed of these fuels.

### 2.4. DATA PROCESSING

The combustion parameters such as IMEP, heat release rate, combustion phase and mass fraction burn (MFB) profiles were calculated by the AVL IndiCom and the AVL Concerto software. In order to convert the particulate number emission from the unit of #/cm<sup>3</sup> to #/kWh, the following equation was used.

$$[PN] = [CC_{PN}] * \frac{1}{\rho_{exh}} * \frac{\dot{m}_{fuel} + \dot{m}_{air}}{Power} * 10^6$$

148 where  $[PN]$  and  $[cc_{PN}]$  is the particulate number emission expressed in the units of #/kWh and #/cm<sup>3</sup>,  
149 respectively.  $\rho_{exh}$  is the density of exhaust in the unit of kg/m<sup>3</sup>, and the temperature and pressure used  
150 for exhaust density calculation was 273 K and 0.1013 MPa, respectively. The reason for using this  
151 temperature and pressure is because the AVL particulate counter and AVL soot sensor calculated the  
152 mass- and number- concentration under this condition.

153 In order to convert the particulate mass emission from the unit of mg/m<sup>3</sup> to mg/kWh, the  
154 following equation was used.

$$155 \quad [PM] = [cc_{PM}] * \frac{1}{\rho_{exh}} * \frac{\dot{m}_{fuel} + \dot{m}_{air}}{Power}$$

156 where  $[PM]$  and  $[cc_{PM}]$  is the particulate mass emission expressed in the units of mg/kWh and mg/m<sup>3</sup>,  
157 respectively.

158 Engine knocking related parameters, such as pressure oscillation and knocking frequency  
159 distributions were calculated by using an in-house Matlab code. In-cylinder pressure oscillation for  
160 each engine cycle was obtained by filtering the raw in-cylinder pressure data by a band-pass filter (3-  
161 30 kHz). Knock intensity in this study is defined as the maximum amplitude of the filtered and  
162 rectified in-cylinder pressure oscillation (MAPO). Frequency distribution of the in-cylinder pressure  
163 was obtained by using the Fast Fourier Transform (FFT) mathematic function. Knock onset is defined  
164 at the first crank angle position where a rapid raise of pressure rise occurred in the pressure oscillation  
165 profile.

166

### 167 3. RESULTS AND DISCUSSION

168 Results of combustion characteristics and fuel economy are provided in this section because they  
169 are significantly important for the understanding of the impact of fuels on internal combustion engines.  
170 In the spark ignition engines, key combustion parameters include combustion delay, combustion



duration, in-cylinder pressure profile and mass fraction profile, which reveal the potential and feasibility of burning specific fuels in SI engines.

### 3.1. COMBUSTION CHARACTERISTICS

Figure 2 presents the full load IMEP of all the fuels under various engine speeds. Clearly, all the fuels delivered the similar maximum IMEP under both the DI and PFI configurations. This is because under the stoichiometric AFR combustion the calorific values of the fuels mixed with 1 kilogram of air are in a narrow range of 2.88-2.91 MJ/kg (see Table 2). Compared to the PFI configuration, the DI configuration led to higher IMEP, which was due to cooling effect of direct injection and more advanced spark timing (see Table 3). For the DI engine configuration at the engine speeds of 3500 and 4500 rpm, fuel enrichment was required to limit exhaust temperatures. The same was true for the PFI engine configuration at the engine speed of 3500 rpm. The IMEP at the engine speed of 1000 rpm was significantly lower than that at the other engine speeds mainly due to the lower boost pressure. For both the DI and PFI configurations, the IMEP at engine speeds of 3500 and 4500 rpm were higher than that of 1800 rpm even though the boost pressure settings were the same, because at higher engine speeds spark timings were more advanced (see Table 3).

Figure 3 presents the knock intensities of all the fuels at full load under various engine speeds. The knock intensity shown in this figure is the averaged MAPO over two-minute measurements. For each engine cycle, in-cylinder pressure oscillation signal was obtained by filtered the in-cylinder pressure by a band filter (3-30 kHz), and then it was rectified. The knock intensity for a given engine cycle is the maximum amplitude of pressure oscillation (MAPO) for that cycle. In the study of engine efficiency improvement through engine design and high octane fuel, Leach et al. [16] defined the MAPO upper limit (engine speed dependent) at 0.09-0.55 MPa over the engine speed of 1000-6000 rpm, which was approximately 0.1 MPa/1000 rpm. The reason that knock upper limits depend on engine speed is because the engine is more tolerated to knocking at higher engine speed due to less time available for auto-ignition.

The knock upper limits used in [16] were also tested in this study. It was found that the engine was operated safely under these knock upper limits, and further increasing the upper limits led to clear increased audible noises. However, the problem of using the MAPO as a parameter is that it varies from cycle-to-cycle significantly, which makes it difficult to control engine knocking. It was found that the averaged MAPO over 50 cycles was a better parameter for monitoring and controlling engine knocking. Obviously, the averaged MAPO over 50 cycles was much lower than the maximum MAPO over the 50 cycles. In this study, the same spark timing calibration optimized for Fuel A was used for all other fuels (see Table 3). The anti-knock ability of fuel is largely dependent on its octane rating and the cooling effect if the direct injection is used. For pure ethanol, some research evidence shows that its cooling effect in DI engines is equivalent up to 18 octane units [17, 18]. In this study, larger differences in knock intensity were observed at the engine speed of 1000 rpm than the other engine speeds, where Fuel A with the least heat of vaporization had the highest knock intensity whilst Fuel E with the highest heat of vaporization had the lowest knock intensity. In SI engines, knocking occurs when auto-ignition happens to end-gas before the normal propagation of flame triggered by ignition. Engine knocking tends to happen in low engine speed and high load regions [19-21].

Figure 4 shows the pressure oscillations of Fuels A and Fuel E at the engine speed of 1000 rpm, and full load condition. In Figure 4, the pressure oscillations for Fuel E have offset by +0.05 MPa. The reason why these two fuels were selected for pressure oscillation analysis was because they were at the two ends of the knocking resistant spectrum among all the fuels. The data presented in Figure 4 was not averaged results from the 200 cycles recorded for each test point, but it was taken from a cycle that had a MAPO closest to the averaged MAPO. The knock onset is a parameter for distinguishing pre-ignition and knocking, and also is used for calculating the knocking delay after the event of ignition. If the knock onset is earlier than ignition, this cycle is defined as a pre-ignition cycle rather than a knocking cycle. In both the DI (Figure 4(a)) and PFI (Figure 4(b)) configurations, it is clear that those cycles are knocking cycles. Fuel A experienced higher pressure oscillations and more advanced knock

onset that those of Fuel E. For example, in the PFI configuration, the knock onset for Fuel A and Fuel E were 24.8 °ATDC and 36.4 °ATDC, respectively. It means that the end gas of Fuel A auto-ignited approximately 12 CAD earlier than that of Fuel E. Another phenomenon should be pointed out is that, knocking intensity quickly raised after the knock onset, and it attenuated gradually due to energy losses as the knock wave propagates and bounces within the cylinder liner.

Figure 5 shows knock intensity probability distributions of Fuels A and Fuel E at the engine speed of 1000 rpm and full load condition. The data in Figure 5 are the statistical analysis of a few hundred of cycles. In both the DI (Figure 5 (a)) and PFI (Figure 5 (b)) configurations, it is clear that compared to Fuel A, Fuel E had a higher knocking distribution in the low knocking intensity region (MAPO < 0.01 MPa), and a lower knocking distribution in the high knocking intensity region (MAPO > 0.01 MPa). For both Fuels A and Fuel E, the probability distribution profile was skewed left, and the probability of high-end knocking intensities was relatively lower compared to the low-end knocking intensities.

When engine knock happens, the auto-ignited gas creates a sudden and violent pressure waves/shocks propagating inside the combustion chamber, leading to resonance of engine parts and audible knocking noises. The resonance frequencies are a function of many factors such as the combustion geometric and the wave media. In passenger car engines, a squat cylindrical combustion chamber experiences radial and circumferential resonance modes [22-24]. The axial modes are neglected because the engine knock happens close to the TDC. A simplified wave equation proposed by Draper [20] and used by many other researchers [22-24] are given as follow :

$$f_{(m,n)} = \alpha_{(m,n)} * \frac{\sqrt{\gamma RT}}{\pi * B} = \alpha_{(m,n)} * \frac{c}{\pi * B}$$

where  $f_{m,n}$  is the knocking frequency for the m (radial) and n (circumferential) mode;  $\alpha_{m,n}$  is the resonance mode factor determined from Bessel functions;  $\gamma$  is the ratio of specific heats; R is the ideal

244 gas constant;  $T$  is the temperature;  $c$  is the sound velocity in the combustion chamber;  $B$  is the  
245 dimension of cylinder bore.

246 The sound velocity for the burned gas/air and fuel mixture in gasoline engines can be roughly  
247 estimated at 950 m/s [25, 26]. The resonance mode factors are 1.84, 3.05, 3.83 and 4.20 when  $(m, n)$   
248 are  $(1, 0)$ ,  $(2, 0)$ ,  $(0, 1)$  and  $(3, 0)$ , respectively [22]. The theoretical resonant frequencies for those  
249 modes mentioned above are 6.57, 10.89, 13.68 and 15.00 kHz, respectively.

250 Figure 6 shows the single-side pressure amplitude spectrum distribution of FFT filtered pressure  
251 for Fuels A and E at the engine speed of 1000 rpm and full load condition. It can be seen that the  
252 pressure amplitudes were much higher at the low frequency region where normal combustion  
253 happened. In both the DI and PFI configurations, there was no peak in the spectrum for Fuel E. In the  
254 DI configuration, peaks existed at the resonant frequencies of 7, 12.4 and 16.6 kHz for Fuel A, which  
255 approximately corresponded to the first radial mode  $(1, 0)$ , the first circumferential mode  $(0, 1)$  and the  
256 third radial mode  $(3, 0)$ . In the PFI configuration, the peak of pressure amplitude spectrum exited at the  
257 7 and 16.6 kHz, which represented the first radial mode  $(1, 0)$  and the third radial mode  $(3, 0)$ . The  
258 deviation between experiment and theoretical resonant frequencies are possibly due to the rough  
259 estimations of sound velocity.

260 The speed of sound was recalculated by minimizing the sum of squared residuals between the  
261 experiment and theoretical resonant frequencies. The recalculated speed of sound was 939 m/s, which  
262 gave the resonant frequencies of 6.7, 14.0 and 15.3 kHz at the first radial mode  $(1, 0)$ , the first  
263 circumferential mode  $(0, 1)$ , and the third radial mode  $(3, 0)$ , respectively. The corresponding  
264 temperature for this speed of sound was 2211 K. For the PFI and DI configurations, the resonant  
265 frequencies at the first radial mode  $(1, 0)$  and the third radial mode  $(3, 0)$  were the same. This shows  
266 that Fuel A started to be auto-ignited at the same temperature (2211 K), regardless of engine  
267 configurations.

Figure 7 presents the combustion delays of all the fuels at full load under various engine speeds. The combustion delay is defined as the crank angle intervals between ignition and 5% of MFB. For the DI configuration, the differences in combustion delays were approximately 1 CAD, and the order is:  $B < A \approx C \approx D < E$ , which matched the order of the HoV. Since the spark timing setting of all fuels were kept the same, the in-cylinder temperature difference at the timing of ignition was mostly due to the cooling effect of fuels, and the fuel with a high HoV led to lower temperature, and thus longer combustion delay. For the PFI configuration, the effect of heat of vaporization was less clear because the fuel was injected in the intake port instead of directly in the cylinder.

Figure 8 presents combustion characteristics of all the fuels at full load under various engine speeds. CA5-90 represents the crank angle interval between 5% and 90% of MFB, which is used to describe the combustion duration. For the DI configuration, the differences in combustion durations (CA5-90) between Fuels B to E and Fuel A were limited (less than 1CAD). When combustion durations (CA5-90) were broken down into CA5-50 and CA50-90, more differences in combustion burning rate were observed in the second-half of combustion (CA50-90), which can be explained as the temperature and pressure during the CA50-90 were much higher than those during the CA5-50, and thus differences in burning rate between fuels would be more obvious. Fuel E had relatively long CA5-90, CA5-50 and CA50-90. The possible explanation is that with Fuel E led to more fuel wetting because it has the highest HoV and the lowest energy density. The boiling point of ethanol is relatively lower than the most of hydrocarbon components in the gasoline, and the HoV of ethanol is much higher than gasoline; therefore, heavy hydrocarbons impinged on the cylinder liner/wall were difficult to be vaporized. Additional optical diagnostics in an optical engine can provide evidence for this assumption.

Figure 9 presents the maximum in-cylinder pressure of all the fuels at full load under various engine speeds. For both the engine configurations, the maximum in-cylinder pressure differences between Fuels B to D and Fuel A were limited ( $< 0.2$  MPa). At 1000 rpm engine speed, Fuel E had 0.5

MPa lower maximum in-cylinder pressure than Fuel A, resulting from a longer combustion duration. The difference in the maximum in-cylinder pressure between the DI and PFI configurations were mainly due to different ignition settings.

Figure 10 presents the normalized ISFC of all the fuels at full load under various engine speeds. The 'normalized ISFC' means the ISFC was normalized by the 42 MJ/kg low calorific value in order to eliminate the difference in low calorific values between fuels. Generally, the difference in the normalized ISFC between Fuel A and Fuels B-E were within 2%. At fuel enrichment operating points, including 3500 and 4500 rpm engine speed in the DI configuration, and 3500 rpm in the PFI configuration, the normalized ISFC were significantly lower than those of at 2500 rpm engine speed where no fuel enrichment was required. It is worth to point out that, in this study insufficient repeats (< six repeats) were conducted; therefore, no statistical significance analysis can be provided regarding the fuel consumption data.

### 3.2. ENGINE OUT EMISSIONS

Figure 11 presents indicated specific gaseous (total HC, CO and NO<sub>x</sub>) emissions for all the fuels at full load under the DI and PFI engine configurations. Overall, gaseous emissions of all fuels at full load were comparable.

There was limited difference in the CO emissions of all the fuels. In both engine configurations, fuel enrichment for the purpose of limiting exhaust temperature led to high CO emissions due to the lack of oxygen for complete combustion. Fuel enrichment, on the other hand, led to low NO<sub>x</sub> emissions due to reduction in combustion temperature. Interestingly, Fuel E produced slightly higher NO<sub>x</sub> emissions than other fuels. The possible reason is that, the low boiling point ethanol (78 °C) promoted the vaporization of light and medium hydrocarbons in Fuel E, making it harder for heavy hydrocarbons to evaporate and form combustible mixtures. In addition, more fuel quantity was

317 injected for Fuel E compared with other fuels due to its low energy density; hence more fuel  
318 impingement/wetting would be anticipated. The two points mentioned above could have caused Fuel E  
319 have more diffusive combustion near the surface of cylinder liner and piston top. The diffusive  
320 combustion potentially encouraged the NO<sub>x</sub> formulation; therefore, Fuel E produced higher NO<sub>x</sub>  
321 emissions. The reason that Fuel E had higher NO<sub>x</sub> emission even at the PFI configuration is that the  
322 engine was running at full engine load, and the fuel injected (PFI) on the intake valves had very  
323 limited time for vaporization especially at high engine speeds, leading to large droplets of fuels  
324 directly flow into the cylinder by the force of intake air movements, which caused cylinder wall  
325 wetting, and diffusive combustions. Fuels B to D consistently produced slightly less HC emissions  
326 than Fuel A in both engine configurations. In the DI engine configuration, Fuel E led to slightly higher  
327 (2%-10%) HC emissions than Fuel A, this also confirmed that Fuel A experienced more diffusive  
328 combustion due to more fuel impingement. It is worthy to point out that a flame ionization detector  
329 (FID) from Horiba MEXA-7100D was used for the measurement of HC emissions. The FID is widely  
330 used for the analysis of THC. However, this type of detector is subjected to reduced sensitivity to  
331 oxygenated hydrocarbon, as reported Wallner [27] and Price et al [28]. For example, the FID's  
332 response factor towards formaldehyde and acetaldehyde are only 0.2 and 0.6 respectively whilst  
333 toluene is 1. Therefore, the HC emissions reported in this study were underestimated for fuels  
334 containing ethanol.

335 Figure 12 presents particulate emissions for all fuels at full load under the DI and PFI engine  
336 configurations. In both engine configurations, Fuels A consistently produced higher PN and PM  
337 emission than Fuels B to D. Fuel E produced similar PN and PM emissions to Fuel A possibly because  
338 of more diffusive combustion mentioned above. There are several publications which reported the  
339 increase of particulate emissions for ethanol blends [29-32]. It is suggested that by optimizing the  
340 combustion chamber and injection spray, it is possible that fuel impingement can be avoided or at least  
341 reduced so that ethanol blends lead to a benefit of reduced particulate emissions [33-35].

342

343

#### 344 4. CONCLUSIONS

345 In this study, four gasoline fuels containing up to 23.5 vol.% GTL naphtha, three of which  
346 contained up to 20 vol.% ethanol contents, were tested in an AVL single cylinder gasoline research  
347 engine. The results were compared with an EN228 compliant gasoline. The tests were conducted under  
348 full load conditions in the engine speed range of 1000-4500 rpm. The following are the conclusions  
349 drawn from this study:

- 350 1. The formulated gasoline fuels were successfully used in a modern gasoline engine without any  
351 hardware modifications. In both DI and PFI engine configurations and full load conditions, these  
352 formulated gasoline fuels led to comparable combustion characteristics and full power output to  
353 conventional gasoline.
- 354 2. At the full load conditions, less than 2% differences in the normalized ISFC were observed  
355 between the formulated gasoline fuels and the conventional gasoline.
- 356 3. Gaseous emissions of the formulated gasoline fuels were similar to, if not lower than that of  
357 conventional gasoline. Therefore, it is suggested that, there needs to be no further modifications  
358 to exhaust three-way catalysts if these gasoline fuels were used in conventional SI engines.
- 359 4. Compared to the conventional gasoline, lower particulate emissions were observed in gasoline  
360 fuels containing up to 15.4 vol.% GTL naphtha and 10 vol.% ethanol.

361

362 It should be noted that the engine performance and emissions of these formulated gasoline fuels were  
363 collectively influenced by GTL naphtha, ethanol and other hydrocarbons. Further investigation is  
364 required to understand the GTL naphtha's impact on combustion and emissions in internal combustion  
365 engines. In this study, due to the limited amount of GTL naphtha available and the time constrain, less



366 than six repeats were conducted for each fuel; therefore, no robust statistical significance analysis can  
367 be provided. Additional repeat tests on this engine and further tests on a wider range of  
368 engines/vehicles would be required to generalize the validity of these findings.

369

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374 (Germany) would like to thank Jakob Beutelspacher and Jan-Henrik Gross for their supports in fuel  
375 blending and engine testing.

## Tables

**Table 1:** Engine specifications

| Parameters                    | Details   |
|-------------------------------|---|
| Combustion system             | 4-valve pent roof spark ignition                              |
| Displacement/bore/stroke      | 454 cm <sup>3</sup> /82 mm/86 mm                              |
| Compression ratio             | 7-14 (variable)   |
| Injection/ Injection pressure | Direct piezo injector/up to 20 MPa;<br>PFI injection/0.45 MPa |
| Ignition system               | Ignition coil   |
| Engine management system      | IAV GmbH – FI2RE  |
| Maximum boost pressure*       | 0.3 MPa   |
| Maximum engine speed          | 6400 rpm  |

\* The maximum boost pressure the engine can take differs, largely depending on the engine compression ratio. The maximum boost pressure (0.3 MPa) stated in this table is for compression ratio of approximately 7.5:1.

**Table 2:** Fuel properties

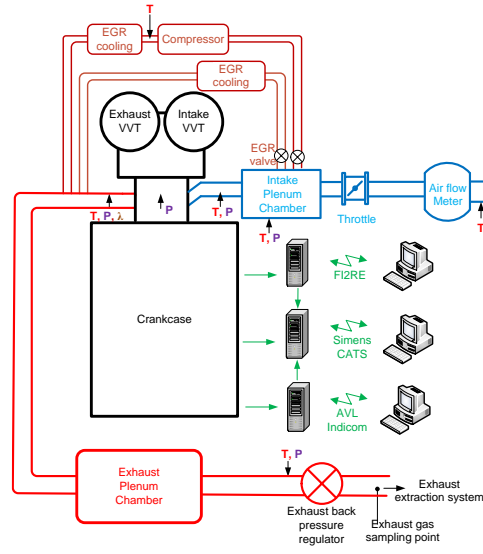
| Fuel                                  | Unit                            | A      | B      | C      | D      | E      | EN228    |
|---------------------------------------|---------------------------------|--------|--------|--------|--------|--------|----------|
| <b>GTL Naphtha</b>                    | vol. %                          | 0      | 7.3    | 11.4   | 15.4   | 23.5   |          |
| <b>Paraffins</b>                      | Vol. %                          | 47.2   | 47.9   | 46.4   | 52.4   | 43.4   |          |
| <b>Olefins</b>                        | Vol. %                          | 10.1   | 11.5   | 8.8    | 9.0    | 0.3    | 18 max.  |
| <b>Aromatics</b>                      | Vol. %                          | 26.0   | 35.22  | 34.9   | 25.6   | 33.0   | 35 max.  |
| <b>Ethanol</b>                        | vol. %                          | 4.7    | 0      | 5.0    | 10.0   | 20.0   | 10 max.  |
| <b>Oxygen Content</b>                 | wt. %                           | 2.3    | 0      | 1.6    | 3.1    | 7.2    | 3.7 max. |
| <b>Density @ 15 °C</b>                | kg/m <sup>3</sup>               | 743    | 749    | 755    | 740    | 767    | 720-775  |
| <b>RON</b>                            |                                 | 95.3   | 96.0   | 95.8   | 96.1   | 96.2   | 95 min.  |
| <b>MON</b>                            |                                 | 85.2   | 85.6   | 84.5   | 86.1   | 86.1   | 85 min.  |
| <b>Stoichiometric AFR</b>             |                                 | 14.17  | 14.47  | 14.15  | 14.09  | 14.53  |          |
| <b>LHV</b>                            | MJ/kg                           | 40.94  | 41.97  | 41.18  | 40.57  | 38.17  |          |
| <b>LHV</b>                            | MJ/L                            | 32.55  | 33.47  | 33.15  | 32.32  | 31.37  |          |
| <b>Vapour pressure</b>                | kPa                             | 57.8   | 54.6   | 56.3   | 55.3   | 50.2   | 45-60    |
| <b>Heat of Vaporization</b>           | kJ/kg                           | 394    | 372    | 401    | 424    | 488    |          |
| <b>LHV</b>                            | MJ/kg <sub>air</sub> at stoic.) | 2.89   | 2.90   | 2.91   | 2.88   | 2.89   |          |
| <b>HoV</b>                            | kJ per MJ energy input          | 9.62   | 8.86   | 9.74   | 10.45  | 12.78  |          |
| <b>Estimated Laminar flame speed*</b> | m/s                             | 0.6944 | 0.6862 | 0.6957 | 0.7049 | 0.7251 |          |

\*The laminar flame speed was estimated under the condition of 1.1 air/fuel equivalence ratio, 0.3 MPa and 177°C initial temperature and pressure. The estimation was done by a Shell's internal model using laminar flame speed data base containing a large amount of common hydrocarbons in gasoline.

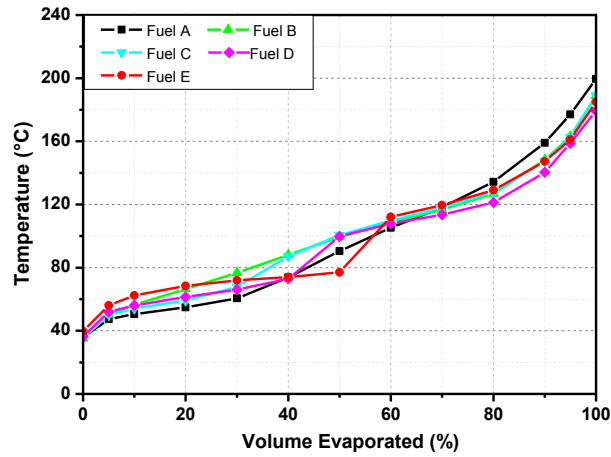
**Table 3:** Full load test protocol

| Engine configuration | Engine Speed | Intake manifold pressure | $\lambda$ | Intake valve open/close timing @ 1mm valve lift | Exhaust valve open/close timing @ 1mm valve lift | Injection timing                   | Intake Tem. | Ignition | Exhaust back pressure |
|----------------------|--------------|--------------------------|-----------|---|--|------------------------------------|-------------|----------|-----------------------|
|                      | rpm          | MPa                      |           | °ATDC   | °ATDC  | °ATDC                              | °C          | °ATDC    | MPa                   |
| DI                   | 1000         | 0.16                     | 1         | 7.8/199.1                                       | -229.4/-18.0                                     | -325; -285;<br>-245; -205;<br>-165 | 38±2        | 2        | 0.16                  |
|                      | 1800         | 0.20                     | 1         | 17.8/209.1                                      | -214.4/-3.0                                      |                                    |             | 2        | 0.20                  |
|                      | 2500         | 0.20                     | 1         | 22.8/214.1                                      | -214.4/-3.0                                      |                                    |             | -3       | 0.20                  |
|                      | 3500         | 0.20                     | 0.85      | 12.8/204.1                                      | -214.4/-3.0                                      |                                    |             | -4       | 0.20                  |
|                      | 4500         | 0.20                     | 0.8       | 2.8/194.2                                       | -214.4/-3.0                                      |                                    |             | -7       | 0.20                  |
|                      |              |                          |           |   |  |                                    |             |          |                       |
| PFI                  | 1000         | 0.16                     | 1         | -7.2/184.2                                      | -209.4/2.0                                       | -492                               | 38±2        | 9        | 0.16                  |
|                      | 1800         | 0.20                     | 1         | 17.8/209.1                                      | -219.4 /8.0                                      | -620                               |             | 4        | 0.20                  |
|                      | 2500         | 0.20                     | 1         | 17.8/209.1                                      | -219.4 /8.0                                      | -679                               |             | -1.5     | 0.20                  |
|                      | 3500         | 0.20                     | 0.85      | 22.8/214.1                                      | -219.4 /8.0                                      | -865                               |             | -2.5     | 0.20                  |

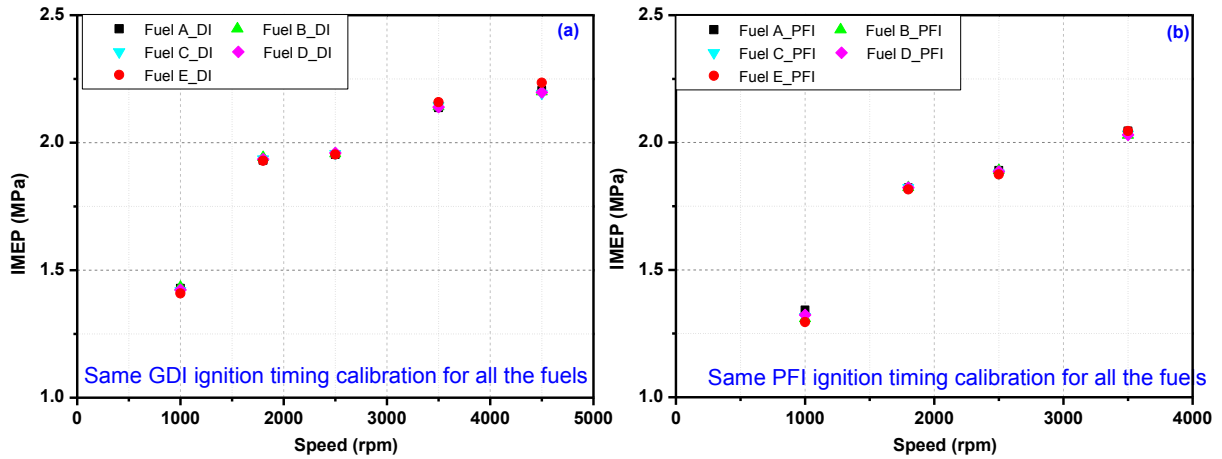
## Figures



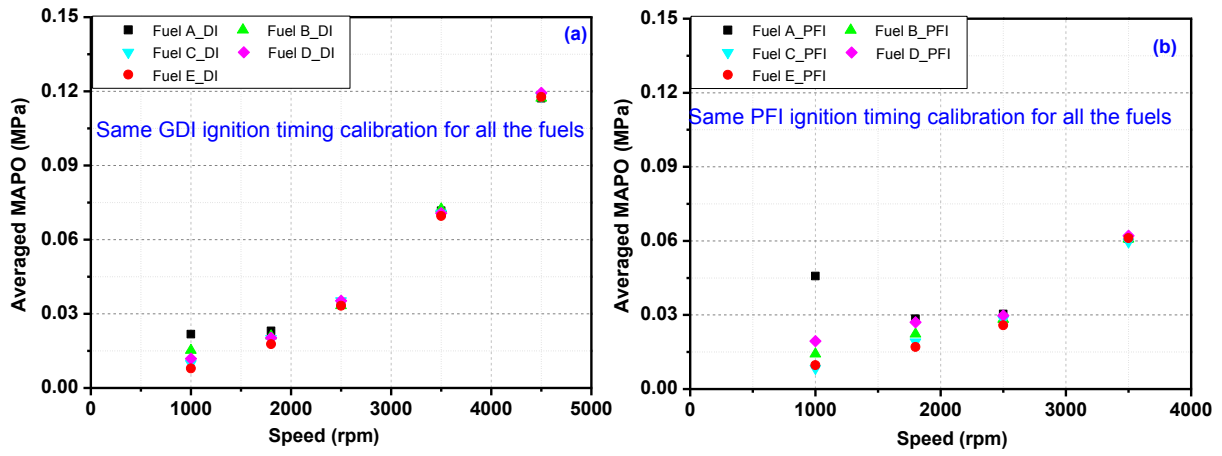
**Figure 1:** Engine setup



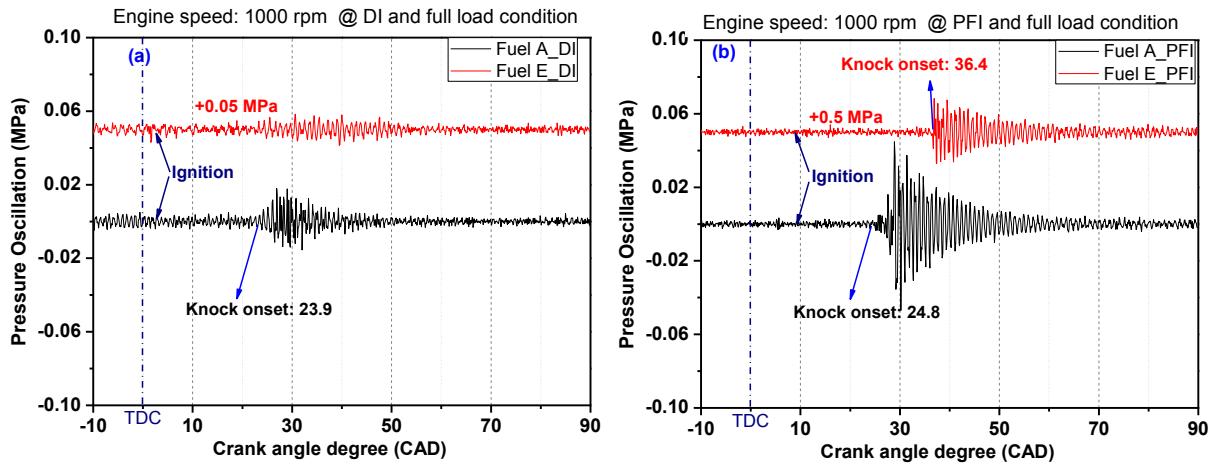
**Ci:** Distillation profiles for all fuels



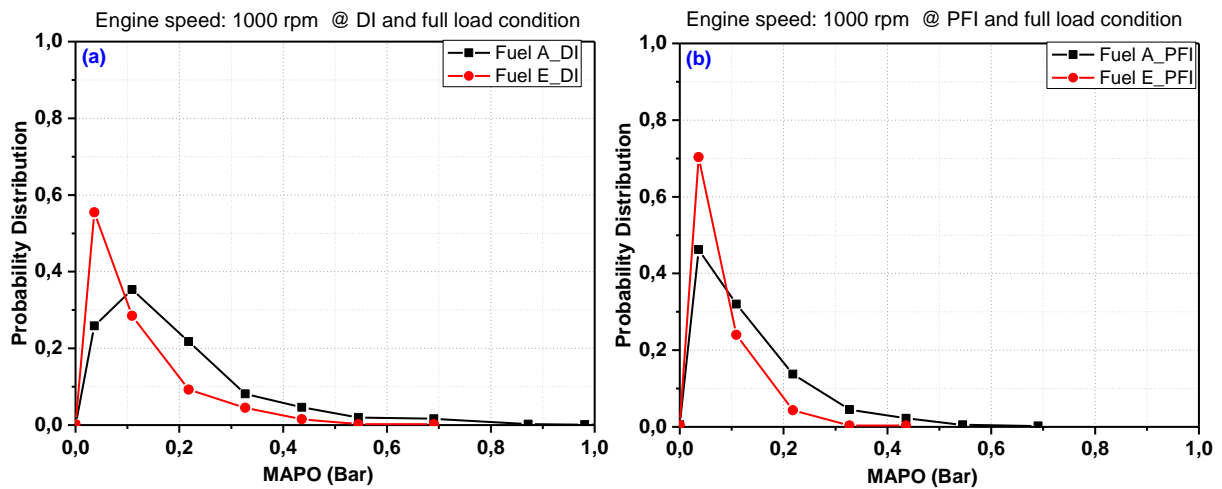
**Figure 2:** IMEP of all fuels at full load: (a) DI configuration; (b) PFI configuration



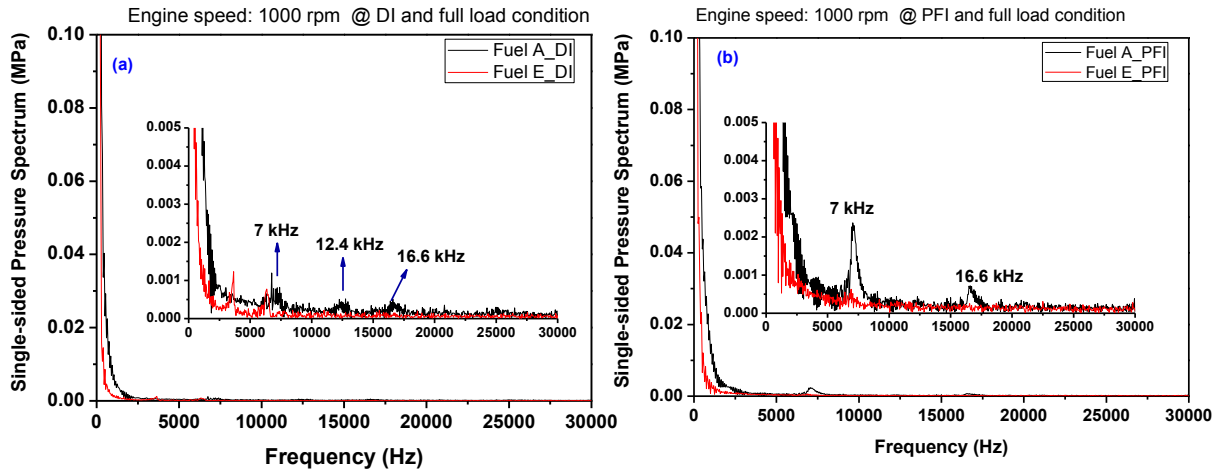
**Figure 3:** Knock intensities of all fuels at full load: (a) DI configuration; (b) PFI configuration



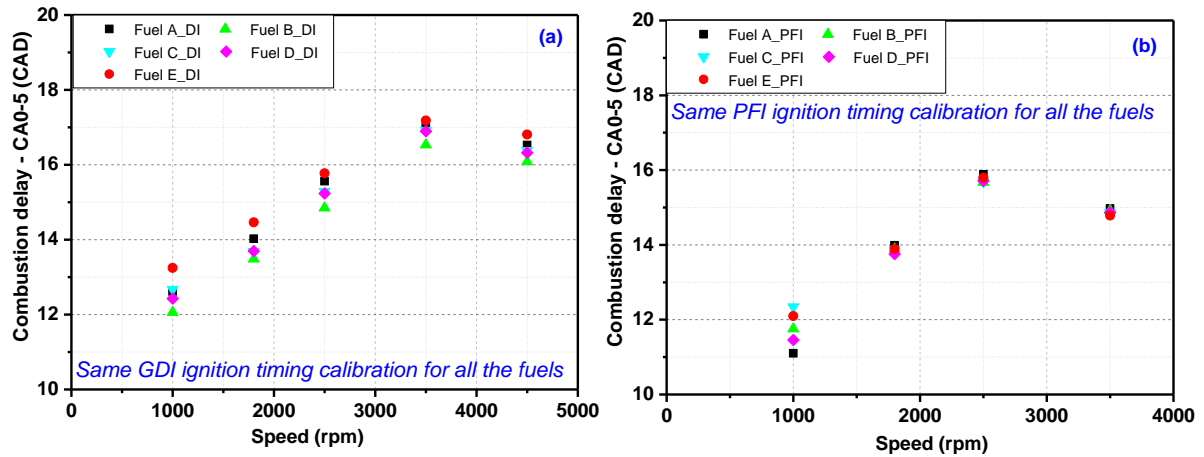
**Figure 4:** Pressure oscillation for Fuel A and E at 1000 rpm engine speed and full load condition: (a) DI configuration; (b) PFI configuration



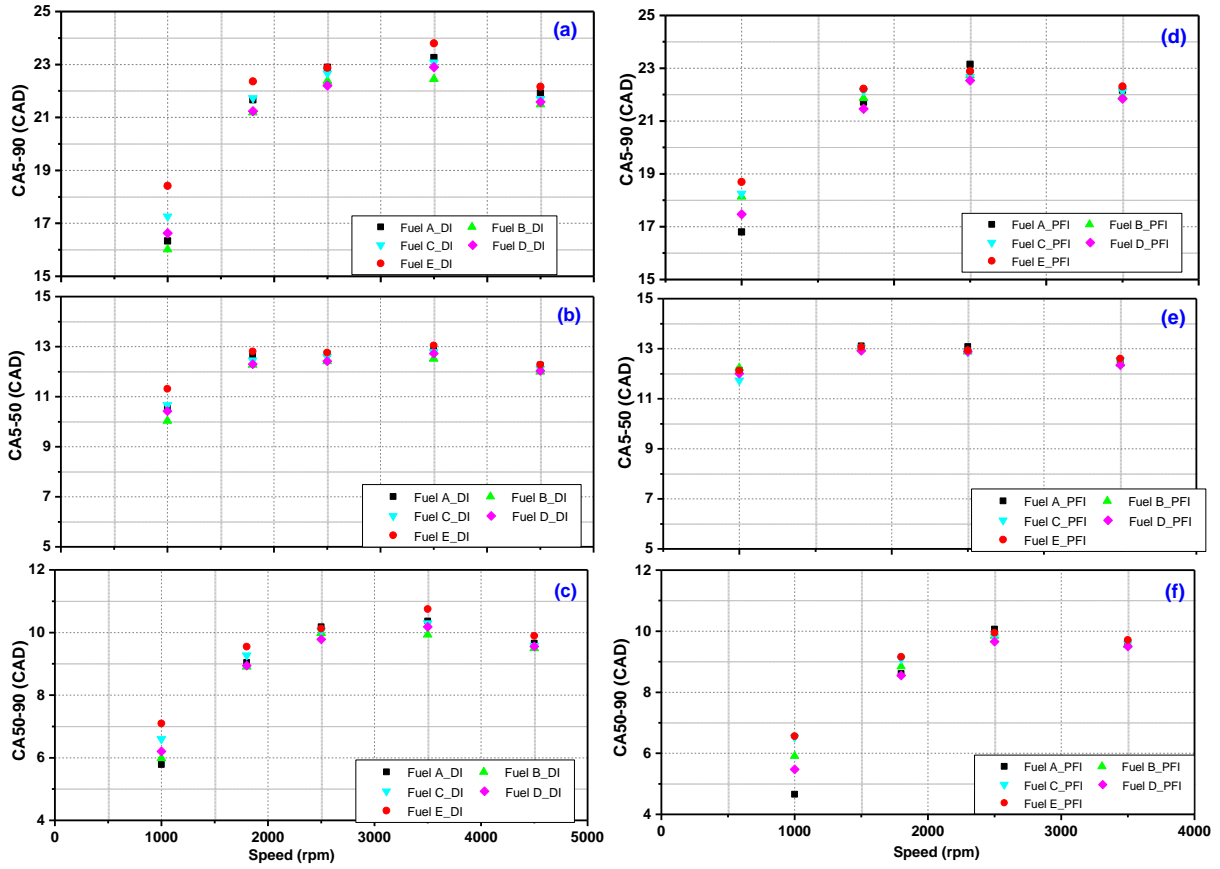
**Figure 5:** MAPO probability distributions for Fuel A and E at 1000 rpm engine speed and full load condition: (a) DI configuration; (b) PFI configuration



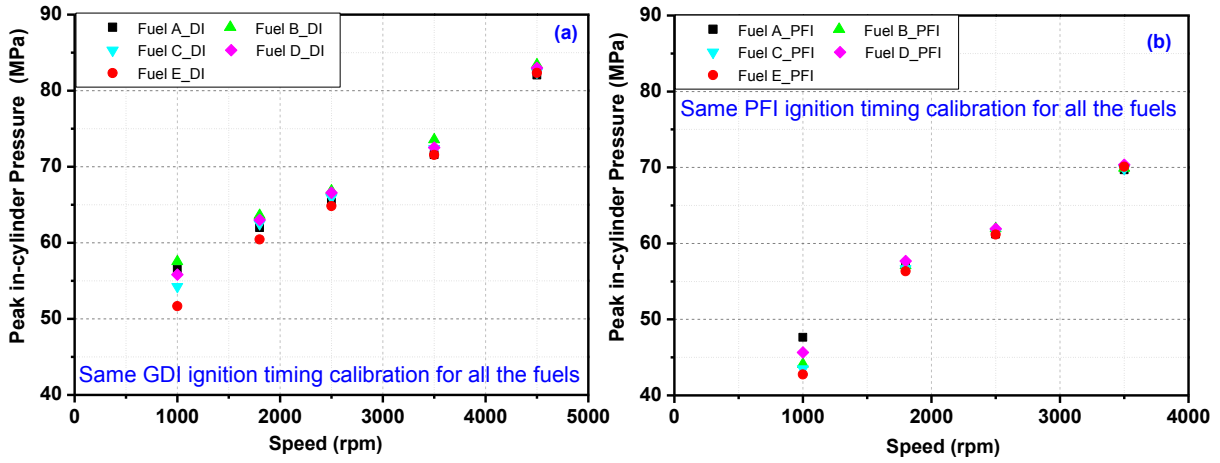
**Figure 6:** Single-side pressure spectrums of FFT filtered pressure traces for Fuel A and E at 1000 rpm engine speed and full load condition: (a) DI configuration; (b) PFI configuration



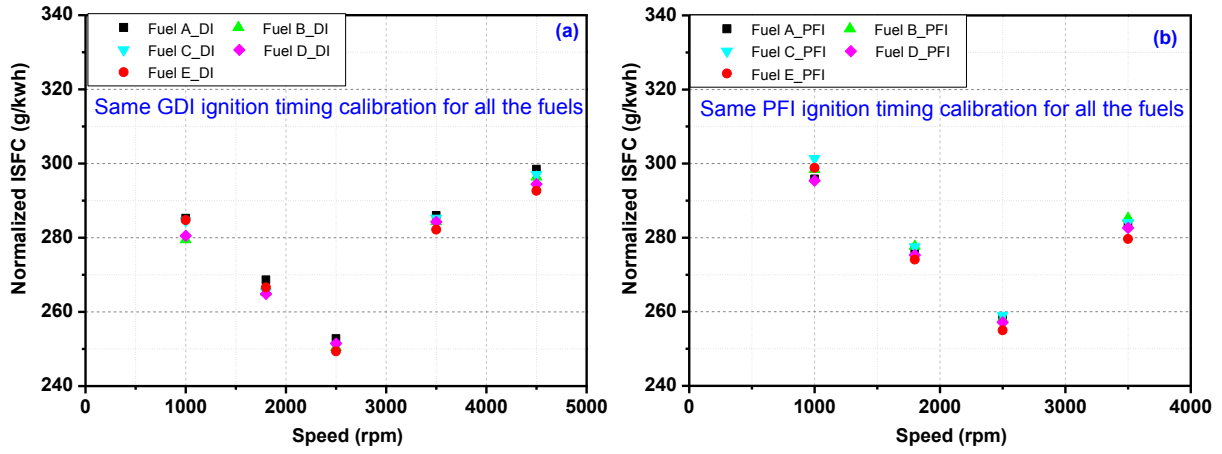
**Figure 7:** Combustion delay of all fuels at full load: (a) DI configuration; (b) PFI configuration



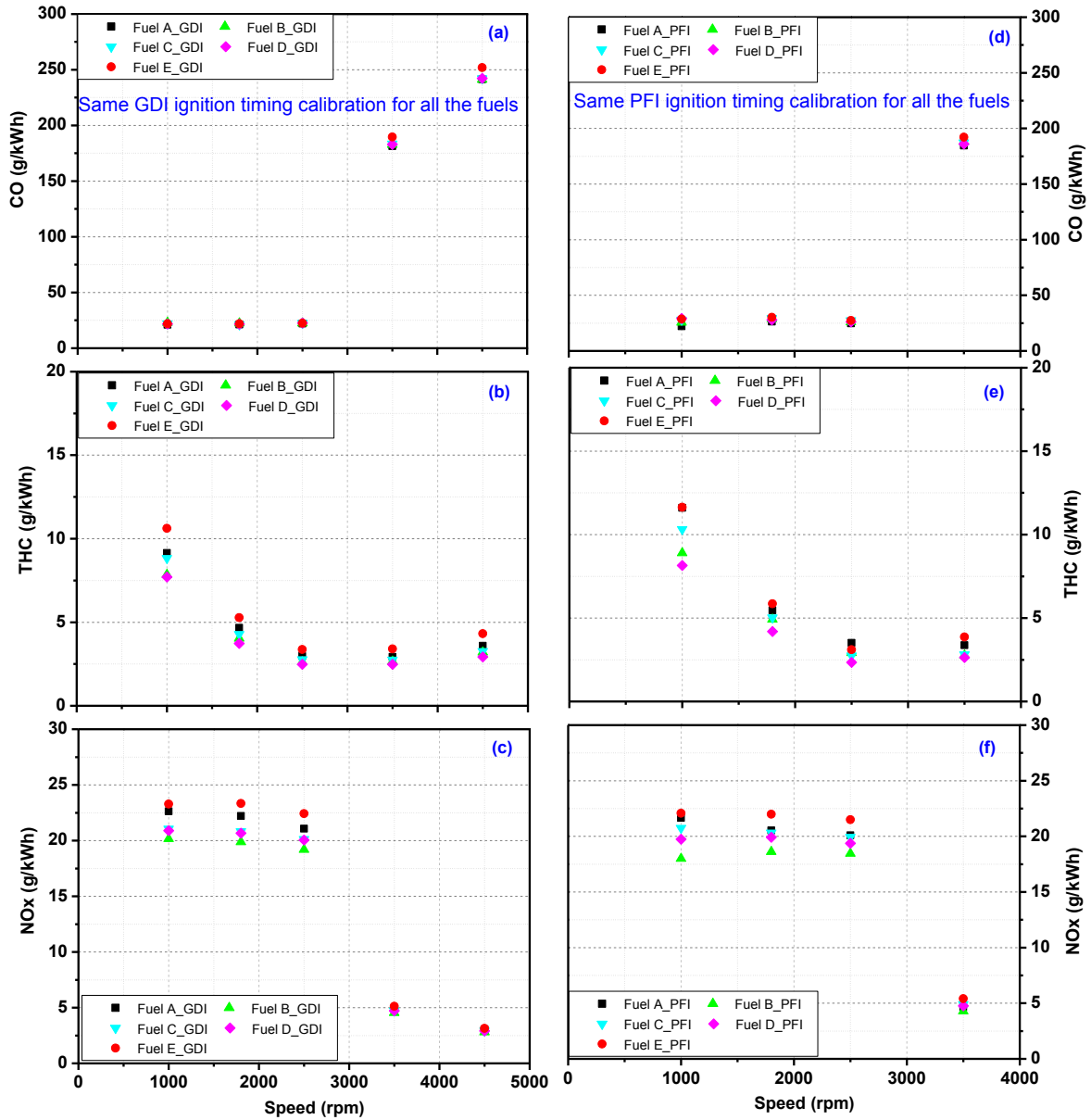
**Figure 8:** Combustion characteristics of all fuels at full load: (a, b and c) DI configuration; (d, e and f) PFI configuration



**Figure 9:** Maximum in-cylinder pressure of all fuels at full load: (a) DI configuration; (b) PFI configuration

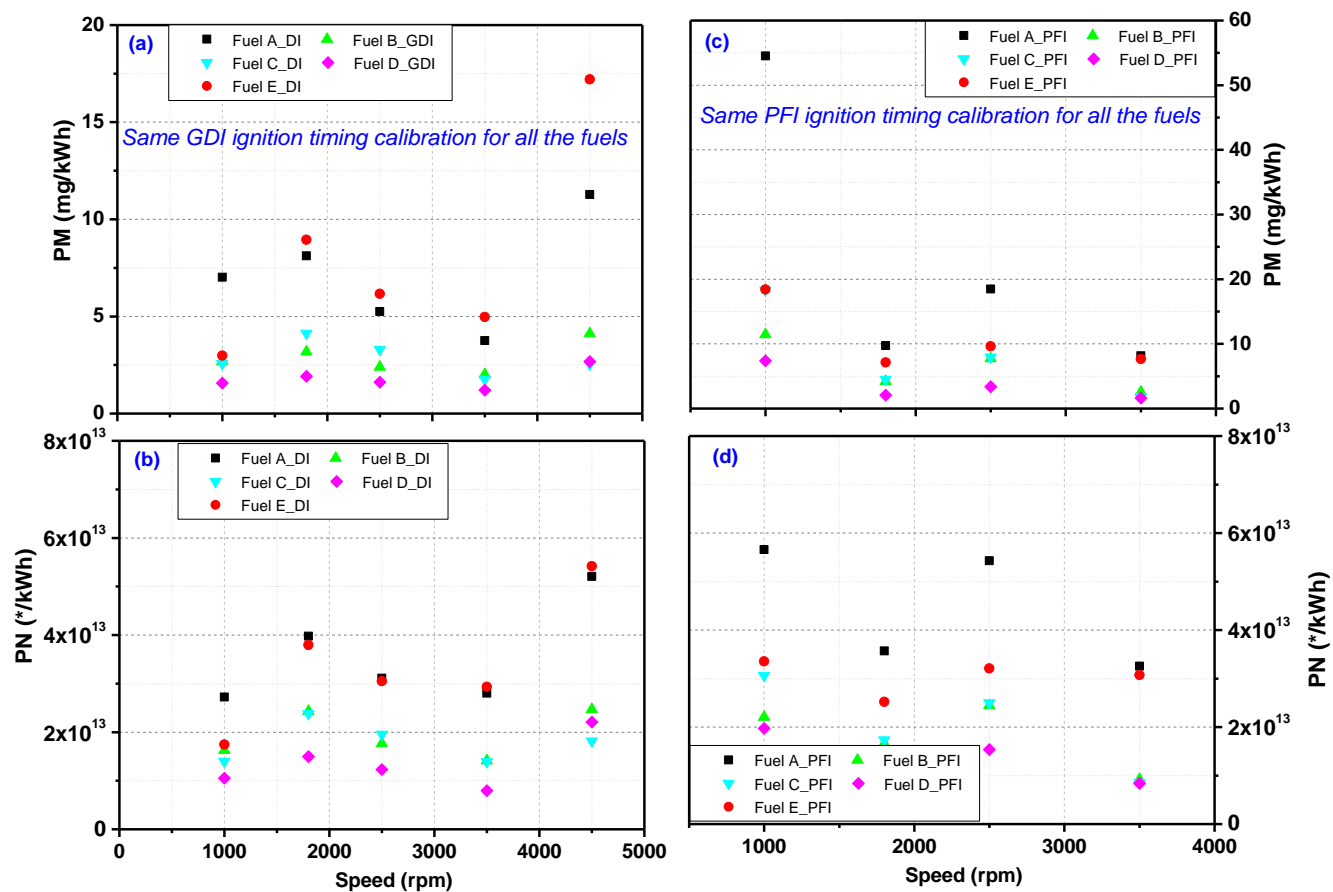


**Figure 10:** Normalized ISFC of all fuels at full load: (a) DI configuration; (b) PFI configuration



**Figure 11:** Gaseous emissions of all fuels at full load: (a, b and c) DI configuration; (d, e and f) PFI configuration





**Figure 12:** Particulate emissions of all fuels at full load: (a and b) DI configuration; (c and d) PFI configuration

## DEFINITIONS, ACRONYMS AND ABBREVIATIONS

|                 |   |
|-----------------|---|
| AFR             | Air Fuel Ratio  |
| ATDC            | After Top Dead Centre   |
| BTDC            | Before Top Dead Centre  |
| CA              | Crank Angle   |
| CA10-90         | Crank angle interval between locations of 10% and 90% cumulative heat release |
| CA10-50         | Crank angle interval between locations of 10% and 50% cumulative heat release |
| CA50            | Crank angle at which 50% of cumulative heat release occurs                    |
| CA50-90         | Crank angle interval between locations of 50% and 90% cumulative heat release |
| CAD             | Crank Angle Degree  |
| CO              | Carbon Monoxide   |
| COV             | Coefficient of Variation  |
| DI              | Direct Injection  |
| EGR             | Exhaust Gas Recirculation   |
| FFT             | Fast Fourier Transform  |
| FID             | Flame Ionization Detector   |
| GTL             | Gas-to-liquid   |
| HoV             | Heat of Vaporization  |
| LHV             | Low Heating Value   |
| THC             | Total Hydrocarbon   |
| IMEP            | Indicated Mean Effective Pressure   |
| MAPO            | Maximum Amplitude of Filtered and Rectified In-Cylinder Pressure Oscillation  |
| MFB             | Mass Fraction Burn  |
| MON             | Motor Octane Number   |
| NO <sub>x</sub> | Oxides of nitrogen  |
| PFI             | Port Fuel Injection   |
| PM              | Particulate Mass  |
| PN              | Particulate Number  |
| SI              | Spark Ignition  |
| rpm             | Revolutions per Minute  |
| RON             | Research Octane Number  |
| VVT             | Variable Valve Timing   |

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